

The representativity index of a simple monitoring network with regular theoretical shapes and its practical application for the existing groundwater monitoring network of the Tychy-Urbanowice landfills, Poland

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Abstract The representativity index R_u is a measure used in assessing the chemical status of groundwater based on monitoring studies. This index is designed to describe the spatial homogeneity of the monitoring network. The general formula for calculating the index R_u includes the following parameters: average distance to the nearest monitoring point, number of monitoring points, and size of the test area. Calculations to determine the representativity index for four different shapes of the theoretical test study with the same area and the same number of monitoring points have been done. These calculations suggest that the index value depends on the shape and the position of these points, and it is less dependent on the size of the surface. An assessment of the representativeness of the monitoring network for the different numbers and configurations of the piezometers around the Tychy-Urbanowice landfills based on the mentioned index has been done as well. The best and the worst configurations of the monitoring network for these landfill sites in mathematical terms have been presented in this paper. The results are surprising: the highest index value is obtained with a single measurement point. The calculations were performed with the area of landfill and the area limited by the range of piezometers as the exclusive test area. To choose the optimal test area, representativity indicator was calculated also for the monitoring network around waste

landfills, including the buffer network behind the piezometers. The difference in the values of the representativity indicator for subsequent variants is astounding. The representativity index for the same monitoring network is about 20 % higher if we consider the test area limited by external piezometers, and higher by another 20 %, taking into account the 95-m buffer zone behind piezometers. Due to increase of the representativity index value with a different width of buffer zone, the mathematical calculations of the monitoring network's representativeness should be supported by an analysis of the geological structure and hydrogeological conditions occurring in the analyzed area.

Keywords Representativity index · Monitoring network · Chemical state of groundwater · Mathematical model

Introduction

The monitoring and representativeness of a sampling of groundwater is a difficult and complex process resulting from the substantial spatial variability of the groundwater composition, limited access to the aquifer and quite frequently, a conceptually inadequate model of the monitoring system with poorly defined recharge and discharge zones.

It has to be mentioned that even in quite simple conditions with a limited spatial variability of groundwater composition, the reliability of three downgradient piezometers can be not appropriate from the point of view of groundwater pollution risk assessment (Witczak et al. 2006).

The monitoring network design depends on the objectives of the monitoring. The basic objective of groundwater quality monitoring is the detection and evaluation of changes in groundwater quality. According to the Water Framework Directive (WFD) of the EU, monitoring should

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control the input of pollutants into the groundwater locally (point sources), and control the status of all groundwater bodies. In both cases, proper monitoring network design should include the same factors (e.g. geology, hydrogeology, recharge and discharge zones, the migration time of contaminants, land use and human impact, regulatory requirements) but could be different in some details, e.g.: the number and location of observation wells, their construction, the sampling frequency and the range of measurements taken according to environmental standards (Witczak et al. 2006). Different approaches have been proposed to establish a representative monitoring network for the abovementioned both cases, but up to now there is no generally accepted methodology (Nielsen 2006; Jousma and Roelofsen 2004; Grath et al. 2001; Quevauviller et al. 2009). For instance, a minimum number of three sampling points in groundwater monitoring network per groundwater body or potential pollution source (Grath et al. 2001; Witkowski 2009) is required.

Methodology

Grath et al. (2001) argued that the monitoring network, to enable a good estimate of the chemical status of groundwater, should be homogeneous, and proposed the following representativity index R_u , as a measure to evaluate this property by mathematical methods. The index is calculated by the formula:

$$R_u = \frac{37.7}{d_{av} \sqrt{\frac{n}{F}}} (\%) \quad (1)$$

where: d_{av} —average distance to the nearest monitoring point (m), n —number of monitoring points, F —size of the test area (m^2).

The idea of this index is quite clear: for homogenous network, locations of monitoring points should be chosen in such a way, that the distance from any point in the area to the nearest monitoring point is small, relatively to the area of the test site. Thus, the higher the ratio, the more homogenous the monitoring network is. The role of the constant in the nominator is to normalize values of index to interval from 0 to 100 %, citing Grath et al. (2001): “For a theoretical network with an optimal triangular pattern of sites the Representativity Index will be 100 %. For sub-optimal (less homogeneous) networks the index will decrease”. However, for a theoretical example of circular area with single monitoring point in the center, we obtain value of representativity index slightly exceeding 100 % (Dąbrowska et al. 2013). Moreover, it is recognized that the monitoring network is representative, if $R_u \geq 80$ % (Rentier et al. 2006).

Substantial difficulty in calculating representativity index is the necessity of determining the value d_{av} —average distance to the nearest monitoring point. In practice, computations are done (by computer) with the following steps:

1. Test area is replaced by a discrete grid of points.
2. For every point from the grid, distances to measurement points are calculated, and the lowest distance is chosen (distance to the nearest measurement point).
3. Value of d_{av} is calculated as a simple arithmetic mean of those lowest distances.

Although there exists the software tool Gwstat (downloadable from <http://www.wfdgw.net>), that allows the calculation of representativity index, for our purposes we have wrote and used the script in R programming language (R Core Team 2015).

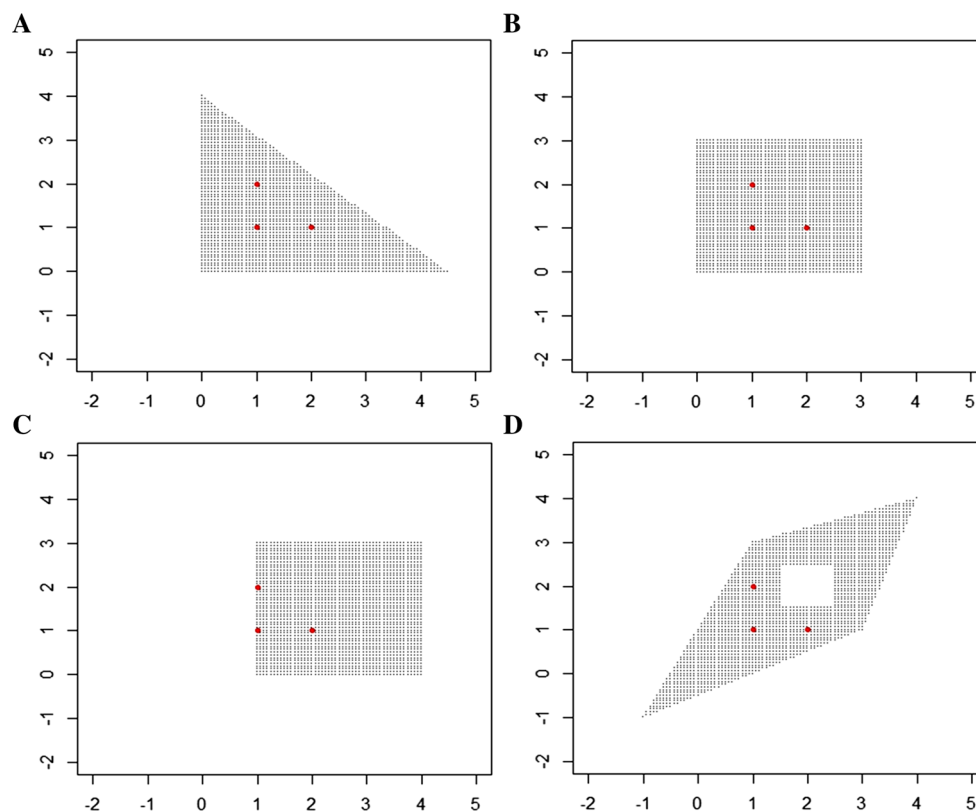
To illustrate the behavior of the representativity index, at first we studied the relationship between different shapes of the area and the value of index. The following shapes were selected (arbitrarily): a triangle, a square (two times) and a deltoid-like shape with square-shaped hole. To ease the comparison of results, their sizes have been set such that areas of all shapes are equal. On these shapes, we put the same configuration of three points to function as a monitoring network. Shapes with configurations of monitoring points are presented on Fig. 1.

The results of the representativity index (R_u) and the mean minimum distance between any point in a given area and the nearest point of measurement (d_{av}) calculation are presented in Table 1.

As we can see, the representativity index depends both on the shape of the study area as well as on the positions of the piezometers within the monitored area. The size of the area itself is not important. The most interesting aspect is the comparison of two squares (Fig. 1b, c). When the monitoring points are located in the central part of the area, the index is higher more than 25 percentage points. In addition, in this case only the value of representativity index is greater than recommended 80 %. Non-central location of monitoring points (Fig. 1c) or irregular shape (Fig. 1d) results in values below 60 %. These examples also show how hard it is to obtain monitoring network meeting the representativity criteria ($R_u \geq 80$ %) for a given area shape, in an intuitive (or naïve) manner.

Applications

In this paper, we tested the possibility of practical use of that index to assess the representativeness of the groundwater monitoring local network of landfills.

Fig. 1 Shapes of the theoretical study areas**Table 1** Results for the considered shapes of the theoretical study areas

Option	R_u (%)	d_{av} (m)
A. Triangle	79.54	0.83
B. Square 1	83.68	0.79
C. Square 2	57.95	1.15
D. Deltoid	57.44	1.15

Study area

System of landfills in Tychy-Urbánowice was selected as an area of research. It is located at the confluence of two surface streams—the Tychy Stream and the Gostynia River in the southern part of Poland. There are two landfills: an active one and an abandoned one (Fig. 2). The old unsealed site had been working since before 1988 as a building materials landfill and later, as a sanitary landfill. This part has been closed in 1994. The new active part covers more than 70,000 m² and consists of two sealed landfills.

The study area is situated in the central part of the Upper Silesian Coal Basin, within the Carpathian Foredeep. There are Carboniferous, locally Triassic, Neogene (Miocene) and Quaternary sediments in the geological profile of the research area. The most important are the Quaternary sediments with the thickness in the range between 12.5 and 17 m. There are Pleistocene river and hollow accumulation sediments (sands, gravels, locally silty clays). The

thickness of the loamy interbedding is equal to about 1–3 m (Witkowski 2006).

There are quite simple hydrogeological conditions in the research area. The hydrogeological profile of the study area is represented by three multiaquifer formations—Quaternary, Triassic and Carboniferous. The most important is a shallow Quaternary sand and gravel aquifer that has been subjected to the negative impact of the old unsealed landfill. Multiaquifer formations located underneath the Quaternary are covered by thick Tertiary clays and are not threatened by the anthropogenic influence. The groundwater flow within the Quaternary aquifer occurs from the north to the south.

Groundwater monitoring of the Quaternary aquifer has worked in this area since 1995. The original network was made at the end of 1993 and the beginning of 1994, and consisted of 14 piezometers (P1, P2, P3, P4, P5, P6, P7, P8, P9, P10, P11, P12, P13, P14) which monitored the old landfill (I) and the new active part (II) (Fig. 2). Before the extension of the active landfill to the second new part (III), 3 piezometers were liquidated (P5, P6, P7) and 3 new were drilled (P5', P15, P16). In 2007–2008, five new piezometers were drilled (P17, P17A, P18, P19, P19A) and up until 2010, the groundwater monitoring network consisted of 19 observation wells (Fig. 2). Finally, as a result of progressive reorganizations, the monitoring network has been divided into two subsystems, which currently involves 15

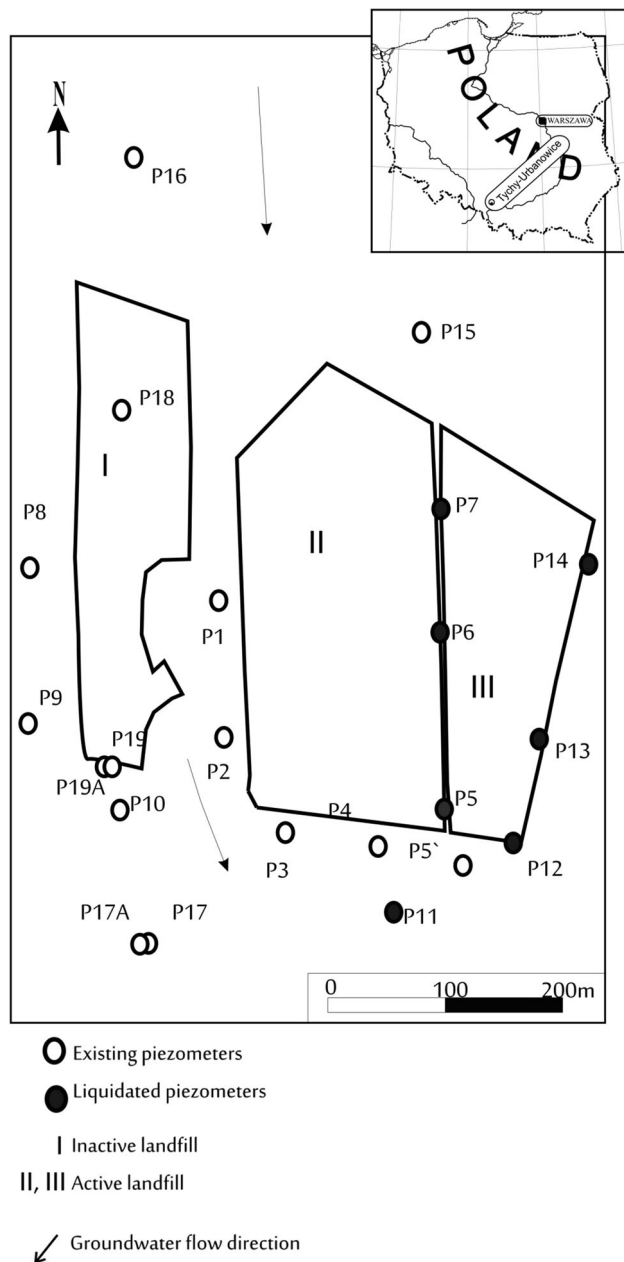


Fig. 2 The system of landfills in Tychy-Urbanowice

piezometers, including two pairs of nested piezometers (P17, P17A and P19, P19A) (Fig. 2). The first subsystem, monitoring area of the inactive landfill, comprises of 11 piezometers—P1, P2, P8, P9, P10, P16, P17, P17A, P18, P19, P19A. Piezometer P18 is particularly important, as it is located on the top of the inactive site. The second subsystem is implemented under the local groundwater quality monitoring of active landfills, and consists of only seven piezometers—P1, P2, P3, P4, P5', P15, P16 (Dąbrowska 2012).

The existing monitoring network was analyzed in terms of its theoretical representativeness considering the effect

of the adopted shape of the research area and the number of observation points on the representativity index's values.

Piezometers within the two nests (P17, P17A and P19, P19A) that are located very close to each other, for the purpose of calculations were treated respectively as two single points (P17 and P19). First, calculations were done for the system of landfills treated as one area (Fig. 3a). Later on, the old landfill (Fig. 3b) and the new landfill (Fig. 3c) were treated as separate areas. In this setting, representativity index has been calculated for every subset of the set of 17 existing piezometers, resulting in 131,071 index values for each of three considered areas.

The calculated index value varies from 21.83 % (for the set of 9 piezometers: P3, P4, P5', P9, P10, P11, P12, P17, P19) to 75.61 % (for single piezometer: P1). The values of R_u for the case where the system of landfills was treated as one area (Fig. 3a) are presented graphically in Fig. 4.

The points in the bottom line correspond to sets of single piezometers, while the point at the top shows the representativity index calculated for all existing piezometers. As we can see, results obtained for the entire area do not indicate any clear relationship between the number of piezometers and the value of the index R_u . Table 2 presents the biggest index value for a given number of piezometers in the monitoring network, and the set of piezometers for which this value was obtained. The highest index value for the whole area is reached not for the set of all piezometers but just for the single piezometer, namely—P1. Moreover, and what is surprising, representativity index seems to decrease for increasing number of piezometers.

To understand thoroughly these results, relationship between the set of piezometers chosen for calculations and the average distance to the nearest piezometer was also investigated. The average distance to the nearest piezometers range between 83.3 and 398.8 m. Results are presented graphically in Fig. 5.

As we can see, in this particular case of existing monitoring network of piezometers, values of the average distance to the nearest monitoring point can be close to minimal (83.5 m) for the subsets consisting of just seven piezometers. Moreover, additional piezometers have no impact on further decrease of this number. Points in the bottom line correspond to single piezometers, and for the P1 piezometer, the average distance to the points of study area is equal to 170.45 m, only twice more than the minimal, resulting in maximal value of representativity index. Of course, the reason for such a behavior may lay in improper (from the point of view of representativity index) location of piezometers, however, we think that it is rather an internal feature of the representativity index.

In accordance with Polish regulations, the monitoring network should consist at least of one upgradient and two downgradient observation wells. Example of such a

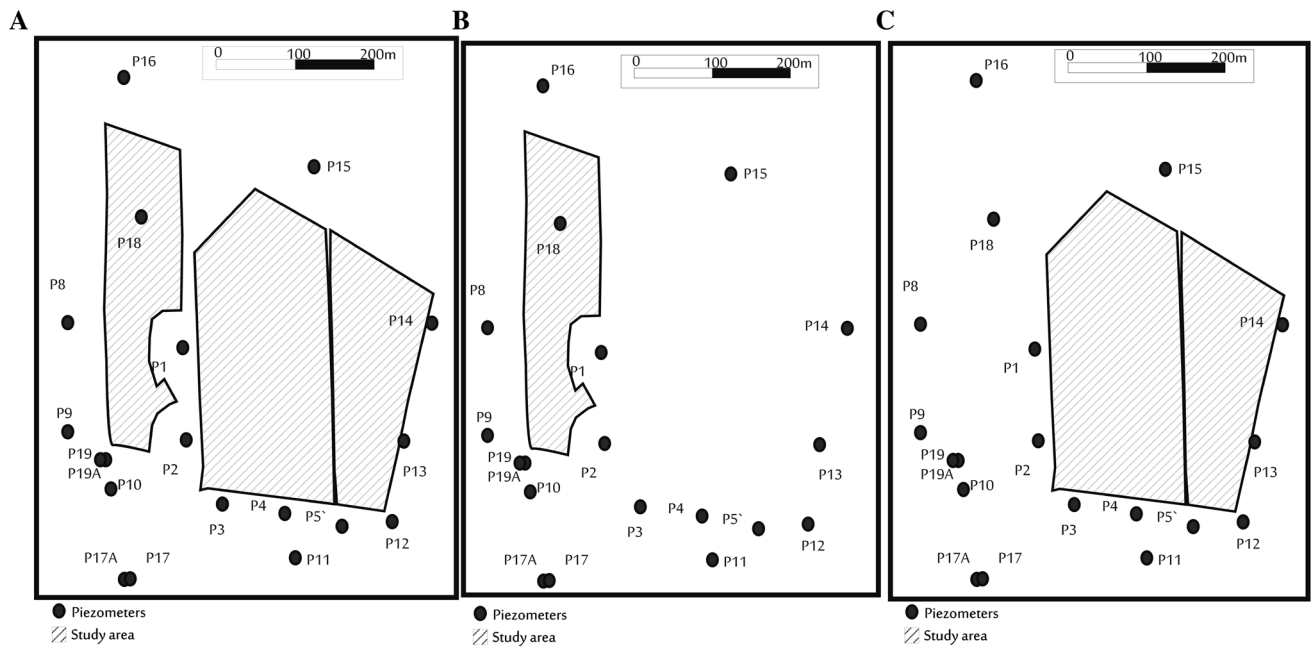


Fig. 3 The shapes of the study areas and piezometers networks: **a** entire area including both the old and active landfills, **b** old landfill, **c** active landfill

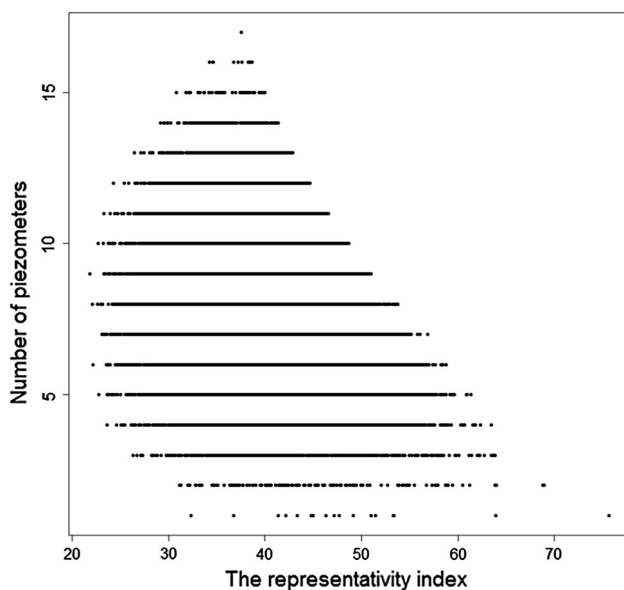


Fig. 4 Representativity index (R_u) value for different subsets of piezometers

network consists of P16 (inflow), P4 and P10 (outflow), for which representativity index is equal to 38.60 %. Another, larger example of network, which seems to be good from the point of view of hydrogeological research is as follows: P15 for the active site, P16 for the old one in the inflow, P3, P5' for the active site, P10, P19 for the old one in the outflow, however, for these 6 piezometers, $R_u = 34.03$ %. Values of representativity index obtained for these two

example networks are very low in comparison to overall maximal value 75.61 %, as well as to values 65.00 and 58.21 %, that can be obtained for networks consisting respectively of 3 and 6 piezometers.

Similar calculations have been made separately for the areas of the old landfill and the new one. Maximal values of representativity index have been obtained for the sets consisting of piezometers:

- P2, P18 for the old landfill, $R_u = 69.46$ %,
- P14 for the new landfill, $R_u = 56.60$ %.

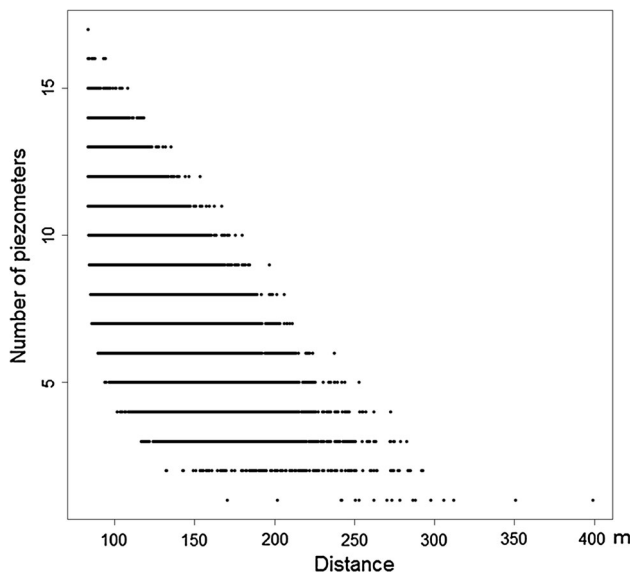
Again, higher representativity index values are obtained for small number of piezometers. When some piezometer is located sufficiently far from the landfill, its addition to given network does not decrease average distance to the nearest measurement point, but increases the number of piezometers, thus lowering the value of representativity index. This way, the minimal values of d_{av} have been obtained for the sets:

- P1, P2, P8, P9, P10, P16, P17, P18, P19 for the old site, $R_u = 39.57$ %,
- P1, P2, P3, P4, P5', P11, P12, P13, P14, P15 for the new site, $R_u = 35.89$ %.

Example networks consisting of a minimum number of three piezometers give us 24.91 % (P10, P16, P19) for old landfill and 41.23 % (P3, P5', P15) for active landfill. These results are summarized in Tables 3 and 4.

Table 2 The maximum value of representativity index for different number of points and the best piezometers set for a given configuration (from 1 to 17 piezometers)

Number of points and piezometer sets	R_u max (%)
1—P1	75.61
2—P1, P13	68.92
3—P2, P14, P18	65.00
4—P1, P4, P14, P18	62.99
5—P1, P2, P13, P14, P18	60.87
6—P1, P2, P13, P14, P15, P18	58.21
7—P1, P2, P4, P13, P14, P15, P18	56.32
8—P1, P2, P4, P13, P14, P15, P18, P19	53.23
9—P1, P2, P3, P4, P13, P14, P15, P18, P19	50.49
10—P1, P2, P3, P4, P5', P13, P14, P15, P18, P19	48.17
11—P1, P2, P3, P4, P5', P8, P13, P14, P15, P18, P19	46.03
12—P1, P2, P3, P4, P5, P8, P9, P13, P14, P15, P18, P19	44.15
13—P1, P2, P3, P4, P5', P8, P9, P10, P13, P14, P15, P18, P19	42.49
14—P1, P2, P3, P4, P5', P8, P9, P10, P12, P13, P14, P15, P18, P19	40.97
15—P1, P2, P3, P4, P5', P8, P9, P10, P12, P13, P14, P15, P16, P18, P19	39.59
16—P1, P2, P3, P4, P5', P8, P9, P10, P11, P12, P13, P14, P15, P16, P18, P19	38.33
17—P1, P2, P3, P4, P5', P8, P9, P10, P11, P12, P13, P14, P15, P16, P17, P18, P19	37.19

**Fig. 5** Average distance to the nearest measurement point (d_{av}) for different subsets of piezometers

The results of calculations of the representativity index (R_u) presented above, performed for the test areas including exclusively the area of landfills demonstrate in general low values of the index, not exceeding 80 %. In this context, it was decided that test areas will be modified (extended) and the influence of such changes on the obtained values of the R_u index determined. This attitude aimed at choosing the variant with an optimal test area and optimal number of monitoring points located within it, for which maximal values of the R_u index were obtained (exceeding the

Table 3 Values of R_u index for the old landfill site (Fig. 3b)

No.	Piezometers sets	R_u (%)
1	P2, P18	69.46
2	P10, P16, P19	24.91
3	P1, P2, P8, P9, P10, P16, P17, P18, P19	39.57

Table 4 Values of R_u index for the new landfill site (Fig. 3c)

No.	Piezometers sets	R_u (%)
1	P14	56.60
2	P3, P5', P15	41.23
3	P1, P2, P3, P4, P5', P11, P12, P13, P14, P15	35.89

suggested 80 %). The calculations were performed for three areas with landfills and surrounding piezometers, i.e. for both landfills (Fig. 6a) $F = 292,621 \text{ m}^2$, for the old landfill (Fig. 6b), $F = 154,656 \text{ m}^2$ and for the new landfill $F = 188,916 \text{ m}^2$.

Optionally, the entire monitoring network was taken into account in the calculations for each of the three areas, together with the network optimal from the hydrogeological point of view as well as the minimal network (consistent with the regulations in force). Results of the R_u factor obtained for subsequent options are relatively high, and fall between 50 and 70 %, however not exceeding 80 % (Tables 5, 6, 7). For example, high value of this factor reaching 70 % was obtained for the variant including all 17 piezometers and this number may be considered optimal from the point of view of the analyzed index.

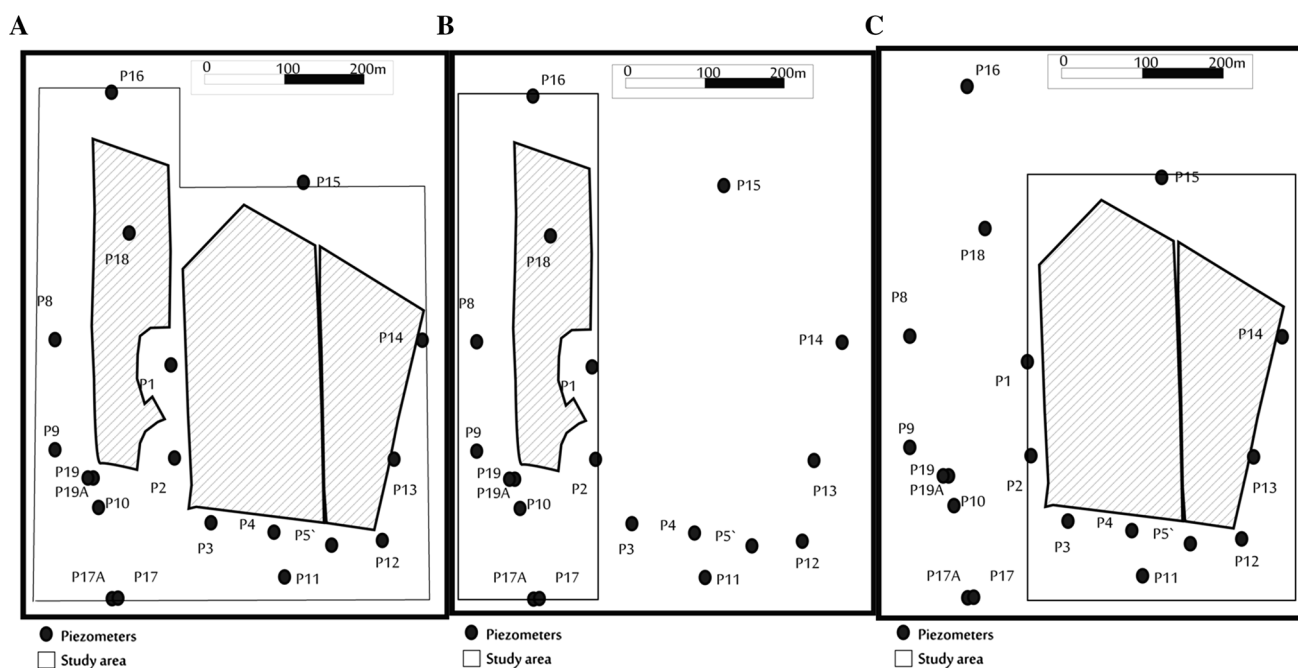


Fig. 6 a–c Extended study areas

Table 5 Values of R_u index for the extended study area of both landfills

No.	Piezometers sets	R_u (%)	d_{av} (m)
1	P1, P2, P3, P4, P5', P8, P9, P10, P11, P12, P13, P14, P15, P16, P17, P18, P19	70.16	70.5
2	P3, P5', P10, P15, P16, P19	66.15	125.86
3	P4, P10, P16	67.72	173.86

Table 6 Values of R_u for the extended study area of the old landfill

No.	Piezometers sets	R_u (%)	d_{av} (m)
1	P1, P2, P8, P9, P10, P16, P17, P18, P19	68.73	71.09
2	P10, P16, P17, P19	56.76	130.6
3	P10, P16, P19	63.72	134.34

In this context, to determine the optimal test area, additional calculations of the values of the R_u index were performed, for the variant including all piezometers, successively extending the test area in relation to the maximal reach of piezometers (Fig. 7). with the buffer strip with the width from 5 to 200 m. The obtained calculation results are presented in Table 8. The results show systematic growth of the value of the R_u index from 0 to 95 m, and its decrease proportionally to the growing distance. For the test area with all piezometers located within it and extended in relation to their maximal reach by a 95-m buffer strip, maximal value of the index exceeding the agreed 80 % (80.41 %) was obtained. In this context, the options with 17 piezometers and the test area described above should be treated as optimal from the point of view of the

representativity of the network, determining its homogeneity.

The study area varied from 217,718 to 721,660 m². Optimal study area is equal to 420,774 m² and the buffer strip with a width of 95 m.

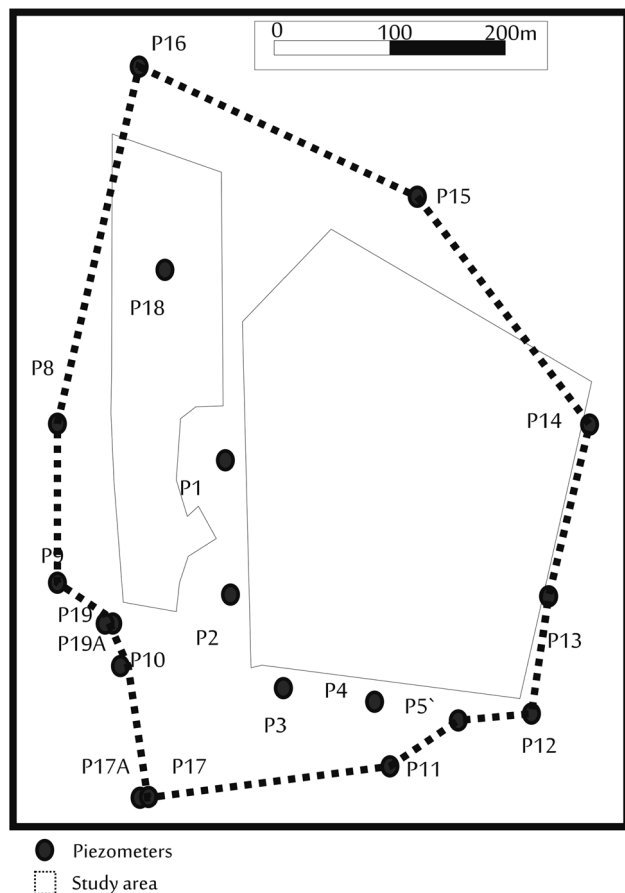
Representativity index was used previously to determine the homogeneity of the monitoring network for the Lipówka landfill (Dąbrowska et al. 2015) and for the Smolnica landfill (Sarga-Gaczyńska 2007). The studies for the first landfill (18,200,000 m²) were carried out with 8 piezometers in Quaternary and 23 piezometers in Triassic aquifer. In the first case, the index R_u of 48.2 % and for the second of 49.9 % were calculated. The monitoring network for the Smolnica landfill (1,300,000 m²) consists of 27 points and gives the R_u index of 72.3 %.

Summary

The representativity index is a measure intended to determine the quality of a monitoring network. However, this index value seems to depend, mainly on the distribution of

Table 7 Values of R_u for the extended study area of the new landfill

No.	Piezometers sets	R_u (%)	d_{av} (m)
1	P1, P2, P3, P4, P5', P11, P12, P13, P14, P15	66.79	77.58
2	P3, P4, P5', P11, P12, P15	56.35	118.71
3	P3, P5', P15	74.75	126.58

**Fig. 7** The study area limited by piezometers network

measurement points and the shape of the study area. The more regular the shape of the test area, the more “representative” the network is. The shape of the test area in the form of a convex polygon allows obtaining greater values of representativity index and for better design of the monitoring network. The results suggest that the representativity index takes into account mostly the homogeneity of the network and in fact, it should be called an index of the network’s homogeneity. Another flaw of this indicator is that it suggests that the number of monitoring points is not important, because in most cases fewer points will give a better representativity index of the network. In most cases, the most homogenous network consists of only one monitoring point.

In the case of the system of landfills as the study area, the highest value of the representativity index

Table 8 The index value for the buffer strip

The width (m)	d_{av}	R_u
0	71.17897	59.8005
5	70.32855	61.7683
10	69.55379	63.71515
15	68.87589	65.61195
20	68.30579	67.44094
25	67.85176	69.18085
30	67.51703	70.8194
35	67.30485	72.34232
40	67.21533	73.7392
45	67.24599	75.00631
50	67.39605	76.13606
55	67.66277	77.12728
60	68.04281	77.98069
65	68.5333	78.69674
70	69.13049	79.28113
75	69.83079	79.73689
80	70.63077	80.0701
85	71.52733	80.28848
90	72.51529	80.39864
95	73.592	80.40873
100	74.75384	80.32702
105	75.99657	80.16121
110	77.31927	79.91949
115	78.71643	79.6094
120	80.18614	79.23853
125	81.72635	78.81344
130	83.33206	78.3416
135	85.00316	77.82865
140	86.73455	77.28078
145	88.52443	76.7035
150	90.37198	76.10093
155	92.27302	75.4782
160	94.22688	74.83892
165	96.231	74.18671
170	98.28368	73.52466
175	100.3833	72.85584
180	102.5263	72.18332
185	104.7149	71.50796
190	106.9426	70.83347
195	109.2108	70.16065
200	111.519	69.49071

($R_u = 75.61\%$) of the monitoring network was received for one point (P1). However, the assessment of the groundwater chemical status using the data from one piezometer, especially in the heterogeneous geochemical conditions within the aquifer, seems to be statistically unjustified and very unreasonable.

The results obtained for different combinations of three points, in accordance with the adequate regulations, indicate that the highest value of the R_u index (41.23 %) is possible to attain for the new landfill and the worst for the old site (24.5 %). The result for the old landfill suggests that the minimal monitoring network consisting of three points is far from being representative, from the point of view of R_u index.

Reasonable, in the context of hydrogeological research, configuration for the whole area (P3, P5', P10, P15, P16, P19), although provides a determination of the groundwater chemical status or could assist in the making of a contour map, but does not give a satisfactory result ($R_u = 34.03\%$).

Calculations were also performed for the test area around the group of landfills, for the monitoring network to be included inside the analyzed area. The calculations were performed for both landfills, for the old landfill and the new landfill. The entire monitoring network was taken into account in the calculations, together with the network optimal from the hydrogeological point of view as well as the minimal network (consistent with the regulations in force).

The difference in the values of the representativity index for subsequent variants (monitoring only for the landfill site and also for the area of landfill with the area limited by the reach of piezometers as the exclusive test area) is astounding. Calculations show that the monitoring network is all the more representative, the more piezometers are located within the study area.

To determine the optimal test area, additional calculations of the values of the R_u index were performed, for the variant including all piezometers, successively extending the test area in relation to the maximal reach of piezometers with the buffer strip. There is quite a big difference in the resulting index value of representativeness for all 17 piezometers when choosing a test area as a dump (37.19 %) and choosing the study area limited by the network of piezometers, taking into account the buffer strip of a certain width (up to 80 %).

However, as this measure may be used as a supporting tool to describe the representativity of the monitoring network, the final assessment should be based on a thorough knowledge of the geological structure and hydrogeological conditions.

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